

Simulation of the October–November 2003 solar proton events in the CMAM GCM: Comparison with observations

K. Semeniuk and J. C. McConnell

Department of Earth and Space Science and Engineering, York University, Toronto, Ontario, Canada

C. H. Jackman

NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

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[1] The FTS instrument on SciSat-I observed over 1 ppmv NO_x in the lower polar mesosphere, in mid February of 2004, more than 100 times normal. Using a middle atmosphere GCM we investigate whether solar proton events or subsequent associated aurorae can explain the NO_x observations. We find that the solar proton events produce insufficient amounts of NO_x , less than 2 ppmv at 90 km. However, it is likely that intense aurorae associated with the Oct.–Nov. 2003 solar storms, and their aftermath, produced thermospheric values of NO_x reaching hundreds of ppmv. In addition, from our simulations we infer that NO_x rich air must have experienced unusually confined polar night descent in the mesosphere in December and January. **Citation:** Semeniuk, K., J. C. McConnell, and C. H. Jackman (2005), Simulation of the October–November 2003 solar proton events in the CMAM GCM: Comparison with observations, *Geophys. Res. Lett.*, 32, L15S02, doi:10.1029/2005GL022392.

1. Introduction

[2] Observations by the FTS instrument on SciSat-I with the Atmospheric Chemistry Experiment (ACE) [Rinsland *et al.*, 2005] show a very large NO_x anomaly at NH polar latitudes during late winter and early spring of 2004. NO_x values as high as 1.3 ppmv are found at 55 km and 80°N in the middle of February in 2004. Typical NO_x concentrations for this region and time are around 6 ppbv. The anomaly has a compact vertical distribution and descends at between 6 and 10 km per month, which is consistent with passive transport by the diabatic circulation. HALOE observes NO_x values of around 40 ppbv at 40 km and 71°N at the beginning of April [Natarajan *et al.*, 2004], which appear to be a remnant of the anomaly observed by ACE.

[3] A suggested source of the NO_x anomaly is the series of major solar proton events (SPEs) during October–November of 2003, which resulted in ionization down to 30 km near the geomagnetic poles [Jackman *et al.*, 2004]. The period of the SPEs was preceded by record X-class X-ray flares and accompanied intense auroral activity, which are additional sources of NO_x production in the thermosphere and possibly the upper mesosphere. X-ray ionization would not have been confined to auroral latitudes. Due to the solar wind pressure from the coronal mass ejections (CMEs) associated with the Oct.–Nov.

2003 solar flares, the Van Allen belts were severely distorted during and after the CMEs so that highly energetic electrons (over 2 MeV) populated the innermost region ($L \leq 2$) [Baker *et al.*, 2004]. Intense auroral activity from these energetic electrons would have resulted in high levels of ionization reaching as low as the upper mesosphere (sec.noaa.gov/tiger). HALOE observed NO_x values over 100 ppmv at 100 km and 75°S in the first week of November, 2003 (haloedata.larc.nasa.gov). Similar NO_x production occurs near both magnetic poles.

[4] Based on GOES observations of solar X-ray and particle fluxes, there appear not to have been additional flares after the Oct.–Nov. 2003 events that had sufficient intensity to directly generate the required amounts of NO_x in the atmosphere (see rsd.gsfc.nasa.gov/goes and www.sec.noaa.gov/weekly). However, there was auroral production following the 2003 flare events. ACE found unusually high values of NO_x , over 10 ppmv, at 90 km and 80°N in February, 2004.

[5] The diabatic circulation in the mesosphere puts a constraint on the distribution of the NO_x source. Wintertime downward transport is less than 10 km/month in the polar region (based on observations of constituent transport and GCMs), so a source located in early November 2003 in the lower thermosphere and upper mesosphere could descend to the anomaly altitude by February of 2004. If the source occurred at a later time, then it would need to be at a lower altitude and this appears to be excluded by the absence of the very energetic ionization events required. Since the photochemical lifetime of NO_x decreases rapidly with increasing altitude it is necessary for NO_x to be confined to the polar night during the period of transport. Randall *et al.* [2005] point out that the unusually strong mesospheric winter polar vortex that developed by mid-January of 2004 and lasted into February could have facilitated such confinement.

[6] The atmosphere was thus ionized through two separate, but related, sources connected with the solar activity of Oct.–Nov. 2003: 1) the high energy protons associated with the SPEs influenced the stratosphere and mesosphere; and 2) the energetic electrons associated with the aurorae from the magnetospheric disturbances and direct solar X-rays influenced the thermosphere and upper mesosphere. To determine whether the first source is sufficient to explain the NO_x anomaly we conducted two simulations with both ionization sources using the Canadian Middle Atmospheric Model (CMAM). The first case is based on the ionization expected from high energy solar protons alone. In the

second case an additional ionization source is included in the thermosphere meant to mimic intense auroral activity accompanying the SPEs.

[7] The model has a spectral dynamical core with truncation set to T32. There are 65 sigma-pressure hybrid levels extending from the surface to between 90 km and 95 km. There is a non-zonal sponge layer in the upper two pressure scale heights of the model (i.e. above 80 km). This sponge formulation avoids unphysical interaction with the circulation at lower altitudes. The model has reasonable agreement with the CIRA-86 climatology inside the sponge layer and in the scale height below (not shown) and exhibits realistic tracer transport out of this region. The CMAM mesospheric and stratospheric climate is realistic as well, so we expect it to have the main dynamical features relevant for NO_x transport. A more detailed description of the model is given by *de Grandpré et al.* [2000, and references therein]. The model has a comprehensive photochemical scheme which includes the relevant NO_x and HO_x reactions. We take our initial state from an arbitrary model year well removed from spinup.

[8] It would be preferable to use an assimilation model for this study, which would be constrained close to the actual circulation of the atmosphere. However, no assimilation models extend above 60 km. Our simulations do not capture the exceptionally strong mesospheric polar vortex that developed during January and February of 2004 [*Manney et al.*, 2005] which is important for the confinement of the NO_x anomaly to the polar night. However, this dynamical state cannot be regarded as a predictable response of the atmosphere to the SPEs since the polar vortex is highly nonlinear and variable. So CMAM should capture a more typical response to the SPEs.

2. Description of the Model Experiment

[9] For the first simulation we limit our ionization source to that due to direct injection of solar protons as measured by the GOES-11 geostationary satellite. NO_x and HO_x production rates were determined from the empirically derived energy deposition rate for the SPEs. The horizontal distribution of the energy deposition rate, E , was approximated by axially symmetric caps centered on the geomagnetic poles with a diameter of about 60 degrees (a smooth transition was assumed between 30 and 35 degrees from the poles). In cgs units the ionization rate, I , is given by $I = 2.8 \times 10^4 \rho E$, where ρ is the air density. The production of HO_x is given by $P_{\text{HO}_x} = A(z) I$, where $A(z)$ is given by *Solomon and Crutzen* [1981]. It is assumed that P_{HO_x} contributes equally to the production of H and OH. Following *Porter et al.* [1976] the production of NO_x is given by $P_{\text{NO}_x} = 1.25 I$, and 45% of P_{NO_x} is assumed to go towards ground state atomic nitrogen production while 55% is assumed to go into $\text{N}(^2D)$. The latter is added to the production of NO and O. NO_x production is quite sensitive to the fractional yield of $\text{N}(^4S)$ in the upper mesosphere and thermosphere [*Rusch et al.*, 1981]. The choice of 45% is motivated by previous modelling studies which have good agreement with observations.

[10] The CMAM simulation was initiated from a time before the SPEs and carried through until the end of March in the following year. The upper boundary condition on

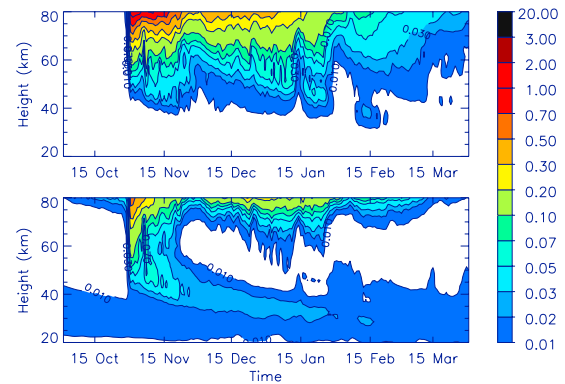


Figure 1. (top) 75 N–90 N average of the passive tracer vs. time for the standard SPEs run (ppmv). (bottom) Same as the Figure 1 (top) but for NO_y . Scale is logarithmic.

NO_x was 1 ppmv in both sets of simulations. For the second case the HO_x and NO_x production was scaled by a factor of the form $1 + 99 \exp(-(z - z_i)/8)^2$, where z_i is the model lid height in log-pressure coordinate kilometers. This was intended to mimic an additional auroral source in the thermosphere during the SPEs. This approximation may overstate the actual contribution of aurorae, which have a complex spatial distribution that does not cover the geomagnetic polar cap uniformly. However, memory of the initial distribution of auroral ionization products will be lost during the descent inside the polar vortex due to advective redistribution. Due to the upper boundary condition, the scaling factor used yielded only a factor of 30 increase of NO_x near 90 km (geopotential height), which is quite conservative.

3. Results

[11] An altitude time series of the NH polar cap averaged (not area weighted) NO_y (defined as $\text{NO}_x + \text{HNO}_3 + \text{HNO}_4 + \text{ClONO}_2 + \text{BrONO}_2$) and a passive tracer having the same initial distribution as NO are shown in Figure 1 for the standard SPEs run (the distributions of NO_y and NO_x are very similar). It is evident from the lower panel that there is a significant amount of photochemical destruction during the descent such that values close to 0.1 ppmv found in the upper panel for the chemically inert tracer do not appear in the lower mesosphere in February. The highest values of NO_x produced during the SPEs are found in the thermosphere and do not exceed 2 ppmv, partly constrained by the upper boundary condition. The initial production is not sufficient to give observed values in the lower mesosphere via transport. We also note that the total column NO_x production integrated over the period of the Oct.–Nov. SPEs is between a factor of 5 to 10 less than the column amount of excess NO_x found in the lower mesosphere in mid-February and this is with no allowance for photochemical loss. This fact in itself points to an additional NO_x source.

[12] There is not enough confinement of the model polar night region to protect high NO_x values as they get transported to lower altitudes. This can be seen in Figure 2 which shows a latitude-time plot of zonally averaged tracer mixing ratio at 0.1 hPa. There is no sharp transition between mid-

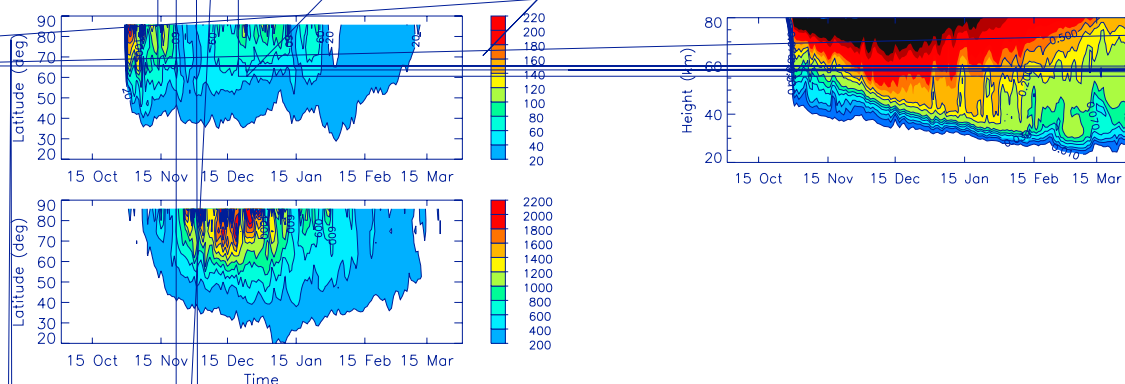


Figure 2. Zonal mean of the passive tracer at 0.1 hPa vs. time in ppbv (top) for the standard SPEs run and (bottom) for the enhanced SPEs run. Both scales are linear but differ by a factor of ten.

latitudes and the polar night, which follows from the fact that the tracer experiences significant horizontal quasi-reversible transport towards mid-latitudes. It is also evident that there are periods when the tracer values in the polar night are no larger than in the sunlit latitudes, in particular, in late November and mid-January. During these periods the horizontal tracer distribution is distributed over a large area with no identifiable polar core region (not shown).

[13] However, there is agreement between the model results in November and December with GOMOS observations of NO_2 in the stratosphere [Seppälä *et al.*, 2004]. Figure 3 shows vertical profiles of NO_2 zonally averaged at 75°N and time averaged over 10 day periods from before the SPEs until late December. These profiles are similar to those shown by Seppälä *et al.* [2004, Figure 2]. Descent of NO_2 produced during the SPEs in the upper stratosphere and lower mesosphere is indicated by the progressively lower altitude of the local maximum above 35 km. Since the

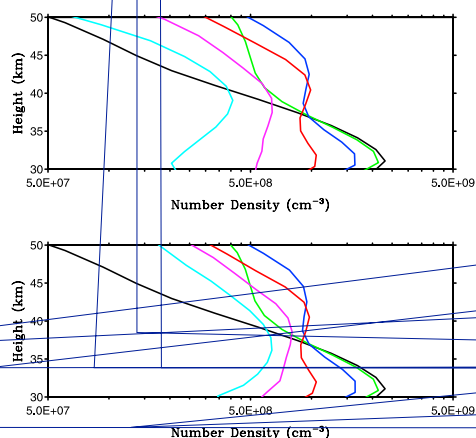


Figure 3. Ten day average profiles of NO_2 averaged over the 70°N–75°N polar ring: (top) results for the standard SPEs run and (bottom) results for the enhanced SPEs case. Black corresponds to Julian days 291–300, green to 301–310, blue to 311–320, red to 321–330, purple to 331–340 and teal to 341–350.

photochemical lifetime of NO_x is much longer than in the mesosphere, differences between model and observations are tied to the transport and the initial NO_x production. Comparing Figures 3 (top) and 3 (bottom), it can be seen that the enhanced SPEs case has higher values of NO_2 in December. In terms of NO_2 and ozone profiles, the results of the enhanced SPEs simulation agree better with GOMOS in the stratosphere than the standard SPEs case. This is due to the more stable stratospheric vortex in the enhanced SPEs simulation, as discussed below.

[14] The results for the run with additional thermospheric NO_x production are shown in Figure 4. Once again there is very little NO_x that survives transport from the thermosphere into the lower mesosphere in February and March (Figure 4 (bottom)). In the stratosphere, slightly higher values of NO_x persist during November and December. This difference is due to a more stable stratospheric vortex in the enhanced SPEs case, as confirmed by analysis of the evolution of PV in the stratosphere (not shown). The descent rate is not sufficient to explain transport of the additional NO_x from above 65 km to below 45 km in under two months. The change in vortex evolution is linked to slight increases in solar heating in the stratosphere due to additional ozone loss above 65 km, which increases ultraviolet radiation absorption below. An ensemble of simulations is needed to determine if this particular dynamical response is accidental or not.

[15] The passive tracer distribution (Figure 4 (top)) has a concentration of about 0.4 ppmv at 60 km in mid-February. This indicates that dilution of polar air in the CMAM simulation was significant, as there was vortex disruption in the mesosphere in January (Figure 2 (bottom)). However, it is the excursion of the polar air into sunlit latitudes that is the dominant loss process of NO_x through photochemical destruction. In general, the mesospheric winter vortex has a different structure compared to the vortex in the stratosphere, which can be seen in the CIRA-86 climatology. Peak zonal winds occur in midlatitudes rather than near the edge of the polar night. This behaviour is due to the dynamical heating associated with strong diabatic descent in the polar region. Thus, the vortex interior is not confined to the polar night. These vortex characteristics are captured by CMAM. It appears that the mesospheric vortex was stronger with a much more confined interior during the 2003–2004 winter, so that both the photochemical process-

ing and dilution of the descending polar air mass were reduced.

4. Discussion

[16] The model simulations presented here fail to reproduce observed NO_x levels in the lower polar mesosphere both because the descending polar air mass experiences significant horizontal disturbances on a regular basis which bring it into regions of daylight and also because the NO_x source appears insufficient. The disturbances which are likely due to gravity and Rossby waves resolved by the model disrupt the polar air mass and prevent the formation of a core that is confined to the polar night for a sufficient duration. The CMAM mesosphere has reasonable agreement with the observed climatology. Under typical conditions, the mesospheric polar vortex is weak and broad (e.g. CIRA-86 zonal wind climatology), and can be readily perturbed by large scale waves. However, the 2003–2004 winter was highly atypical with strong mesospheric westerlies developing by mid-January and persisting into mid-February [Manney *et al.*, 2005].

[17] The mesospheric diabatic circulation is governed primarily by gravity wave drag. If the zonal flow in the stratosphere is westerly then gravity waves with westerly zonal phases are filtered out at critical lines such that mostly easterly phase gravity waves reach the mesosphere and produce easterly drag [Holton, 1982]. Similarly, the sign of mesospheric gravity wave drag reverses when the zonal flow becomes easterly in the stratosphere. Strong westerlies in the stratosphere give rise to strong easterly gravity wave drag in the mesosphere, which drives a stronger poleward diabatic circulation. Conversely, stratospheric warmings cause mesospheric cooling by reducing easterly gravity wave drag and polar diabatic descent. Major warmings lead to the development of westerly drag when stratospheric winds reverse. This westerly drag reverses the zonal flow and the diabatic circulation in the lower thermosphere and upper mesosphere [Liu and Roble, 2002].

[18] Based on the above, it is likely that the upper mesosphere and lower thermosphere winter polar region was experiencing ascent in January and February of 2004 during the unusual major warming which persisted for over four weeks. The descent at lower mesospheric altitudes inside the strong polar vortex would also be weaker. The ACE NO_x measurements appear to be consistent with this view since for about a week after February 15, 2004, there is very little descent of the anomaly. As the stratospheric westerlies recover by late February and the mesospheric westerlies weaken, the descent increases to about 6 km/month. The anomalously strong vortex only lasted about a month during which time it is unlikely that there was more than 6 km of descent in the middle and lower mesosphere. So high values of NO_x must have been present at middle mesospheric altitudes (around 65 km) before the formation of the strong vortex in mid-January 2004.

[19] Although there is little direct information available concerning the circulation in the upper mesosphere from the middle of November 2003 into January of 2004, it does appear that high values of NO_x were transported to middle mesosphere altitudes during this time from the lower thermosphere or upper mesosphere. The HALOE observa-

tions in the southern hemisphere polar region in early November 2003 give an indication of NO_x values in the northern hemisphere. Taking into account the opposite sign of the upwelling in polar region of both hemispheres, there could have been close to 100 ppmv of NO_x around 90 km. Absent other sources at later times, NO_x produced in the lower thermosphere in November was the source of the lower mesosphere NO_x anomaly in February 2004. This requires that the mesospheric winter polar vortex was much less disturbed than was the case in our CMAM simulations from mid-November to early January so that NO_x remained in the dark.

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References

- Baker, D. N., S. G. Kanekal, X. Li, S. P. Monk, J. Goldstein, and J. L. Burch (2004), An extreme distortion of the Van Allen belt arising from the 'Halloween' solar storm in 2003, *Nature*, **432**, 878–881.
- de Grandpré, J., S. R. Beagley, E. Griffioen, J. C. McConnell, and A. S. Medvedev (2000), Ozone climatology using interactive chemistry: Results from the Canadian Middle Atmosphere Model, *J. Geophys. Res.*, **105**, 26,475–26,491.
- Holton, J. R. (1982), The role of gravity wave induced drag and diffusion in the momentum budget of the mesosphere, *J. Atmos. Sci.*, **39**, 791–799.
- Jackman, C. H., M. T. DeLand, G. J. Labow, E. L. Fleming, D. K. Weisenstein, M. K. W. Ko, M. Sinnhuber, J. Anderson, and J. M. Russell (2004), The influence of the several very large solar proton events in years 2000–2003 on the neutral middle atmosphere, *Adv. Space Res.*, in press.
- Liu, H.-L., and R. G. Roble (2002), A study of a self-generated stratospheric sudden warming and its mesospheric-lower thermospheric impacts using the coupled TIME-GCM/CCM3, *J. Geophys. Res.*, **107**(D23), 4695, doi:10.1029/2001JD001533.
- Manney, G. L., K. Krüger, J. L. Sabutis, S. A. Sena, and S. Pawson (2005), The remarkable 2003–2004 winter and other recent warm winters in the Arctic stratosphere since the late 1990s, *J. Geophys. Res.*, **110**, D04107, doi:10.1029/2004JD005367.
- Natarajan, M., E. E. Remsberg, L. E. Deaver, and J. M. Russell III (2004), Anomalous high levels on NO_x in the polar upper stratosphere during April, 2004: Photochemical consistency of HALOE observations, *Geophys. Res. Lett.*, **31**, L15113, doi:10.1029/2004GL020566.
- Porter, H. S., C. H. Jackman, and A. E. S. Green (1976), Efficiencies for production of atomic nitrogen and oxygen by relativistic proton impact in air, *J. Chem. Phys.*, **65**, 154.
- Randall, C. E., et al. (2005), Stratospheric effects of energetic particle precipitation in 2003–2004, *Geophys. Res. Lett.*, **32**, L05802, doi:10.1029/2004GL022003.
- Rinsland, C. P., C. Boone, R. Nassar, K. Walker, P. Bernath, E. Mahieu, R. Zander, J. C. McConnell, and L. Chiou (2005), Trends of HF, HCl, CCl₂F₂, CCl₃F, CHClF₂ (HCFC-22), and SF₆ in the lower stratosphere from Atmospheric Chemistry Experiment (ACE) and Atmospheric Trace Molecule Spectroscopy (ATMOS) measurements near 30°N latitude, *Geophys. Res. Lett.*, doi:10.1029/2005GL022415, in press.
- Rusch, D. W., J.-C. Gérard, S. Solomon, P. J. Crutzen, and G. C. Reid (1981), The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere—I. Odd nitrogen, *Planet. Space Sci.*, **29**, 767–774.
- Seppälä, A., P. T. Verronen, E. Kyrola, S. Hassinen, and L. Backman (2004), Solar proton events of October–November 2003: Ozone depletion in the Northern Hemisphere polar winter as seen by GOMOS/Envisat, *Geophys. Res. Lett.*, **31**, L19107, doi:10.1029/2004GL021042.
- Solomon, S., and P. Crutzen (1981), Analysis of the August 1972 solar proton event including chlorine chemistry, *J. Geophys. Res.*, **86**, 1140–1146.

C. H. Jackman, NASA Goddard Space Flight Center, Code 916, Building 22, Room E318, Greenbelt, MD 20771, USA.

J. C. McConnell and K. Semeniuk, Department of Earth and Space Science and Engineering, York University, Toronto, ON, Canada M3J 1P3. (kirill@nimbus.yorku.ca)